Acoustic Actuation of Vapor-Liquid Interfaces in Boiling and Condensation Processes

Thomas R. Boziuk, Marc K. Smith, and Ari Glezer

School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA

Presented By

Marc K. Smith

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Huntsville, AL

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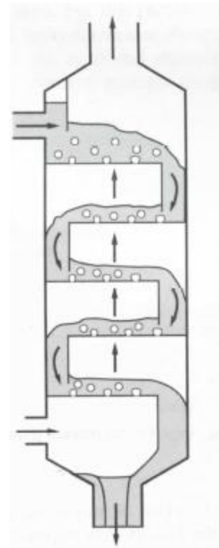
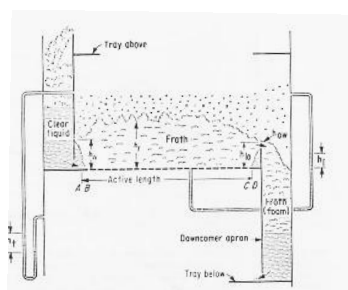
Two-Phase Power Dissipation Applications

Server Farm



Insulated-Gate Bipolar Transistor

Radar

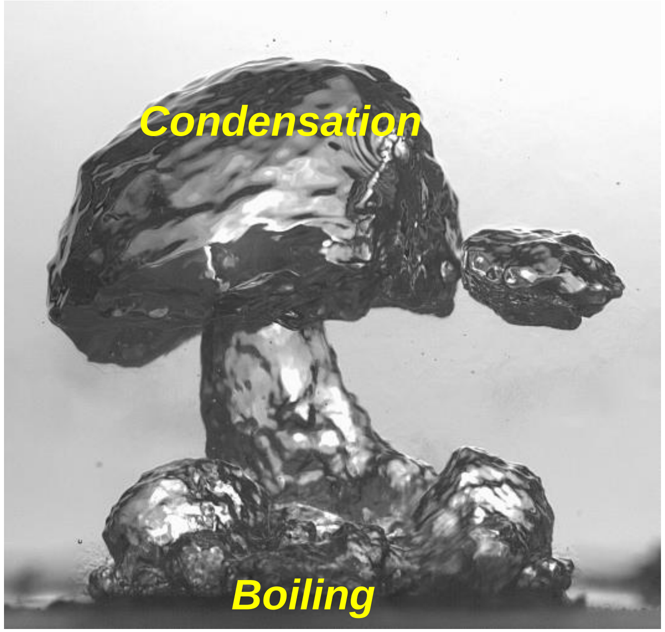


Chemical / Process Engineering

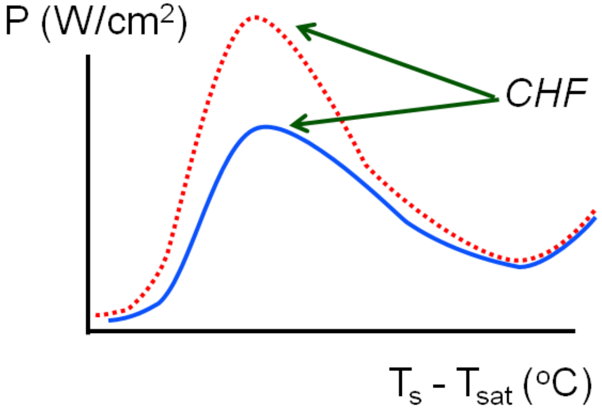
Electric Vehicle Drivetrains

Control of Phase Change Heat Transfer

- Boiling heat transfer for high-power, dense electronic systems
- Heat transfer is limited by two primary processes
  - » Vapor formation and removal rates (critical heat flux)
  - » Condensation rate
- Boiling and condensation present different design challenges
  - » Boiling: increase CHF, decrease surface superheat
  - » Condensation: enhance in bulk fluid for efficient thermal packaging
- Acoustic control of 2-phase boiling processes
  - » *At heater surface* control of vapor growth, spreading, and advection
    - – Surface force engendered by high-frequency ultrasound
    - – Used in conjunction with complex boiling geometries
  - » *In bulk fluid* control of condensation
    - – Acoustic actuation couples to surface Faraday waves ***or*** via radiation pressure force and droplet ejection
    - – Pool boiling and nozzle condensation geometries

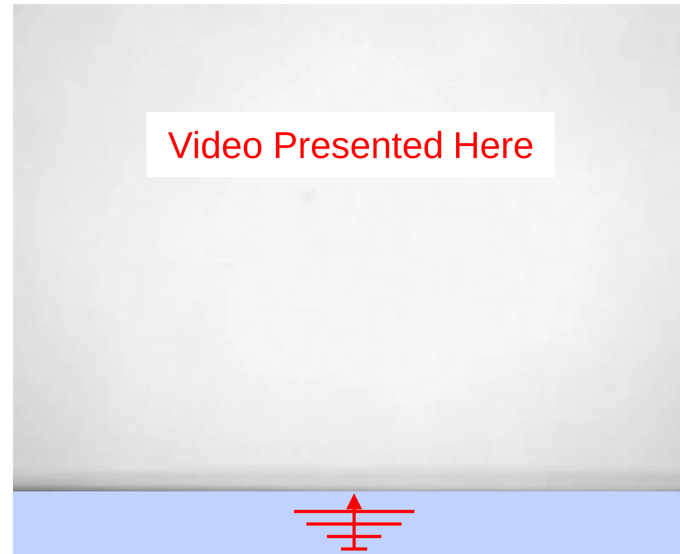


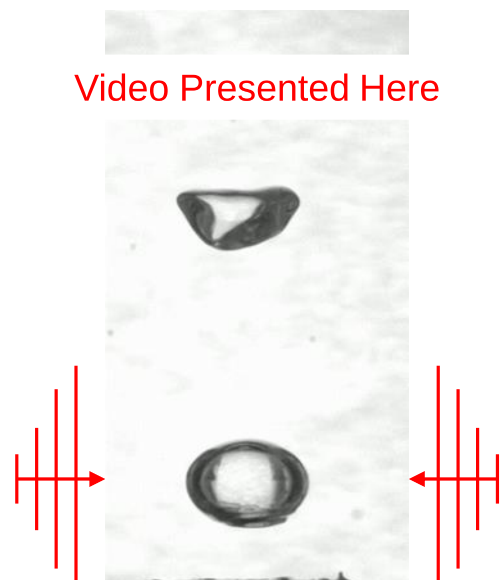
1 mm



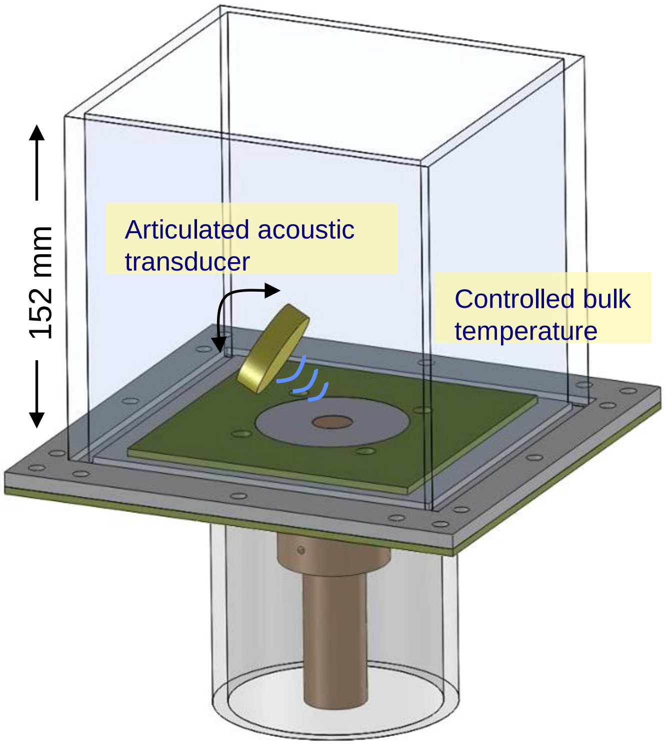
Acoustic Actuation of Liquid/Gas Interface

- Interfacial coupling varies substantially with actuation wavelength
- Ultrasonic [O(1 MHz)] liquid/gas interfacial actuation
  - » ***Short actuation wavelength*** [O(1 mm)]
    - – Exploits acoustic surface force to effect interfacial deformations and injection of a liquid jet and droplets
  - » λ_{acoust} = 0.9 mm; D_{res} = 2 μm; $\lambda_{capillary}$ = O(μm)
  - » Impedance mismatch
    - – $Z_{vapor}/Z_{water}=1.8\times10^{-4}$
  - » High acoustic absorption coefficient
    - – $\alpha_{H2Ovapor} \approx 1{,}000\ \alpha_{H2Oliquid}$
  - » Amplitude = $6.82\cdot10^3$ kPa peak-to-peak
  - » Forcing affects vapor bubbles larger than D_{res}
- O(1 kHz) liquid/gas interfacial actuation
  - » ***Long actuation wavelength*** [O(1 m)]
    - – Much larger than the characteristic length scale of the vapor bubbles [O(5-10 mm)]
    - – Forces capillary surface waves to enhance mixing of the interfacial thermal boundary layer
  - » λ_{acoust} = 1.5 m; D_{res} = 5.5 mm; $\lambda_{capillary}$ = O(mm)
    - – Significant disturbances
  - » Amplitude = 5 kPa peak-to-peak
  - » Bjerknes body forces affect bubble's path

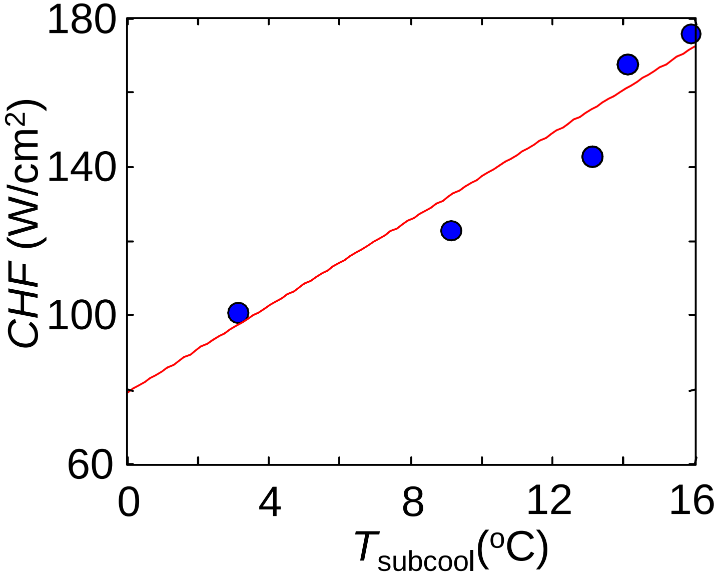




Acoustically Controlled Boiling: Experimental Setup



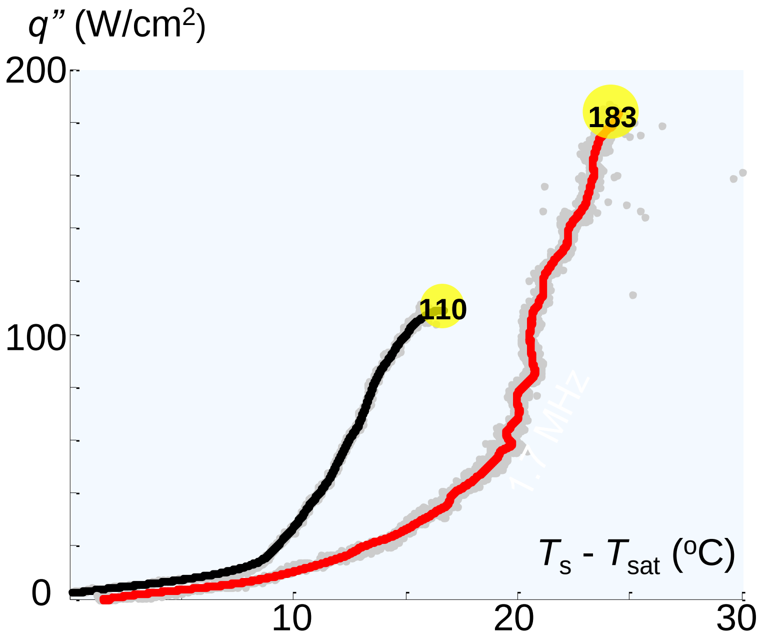
Variation of Critical Heat Flux with Bulk Temperature

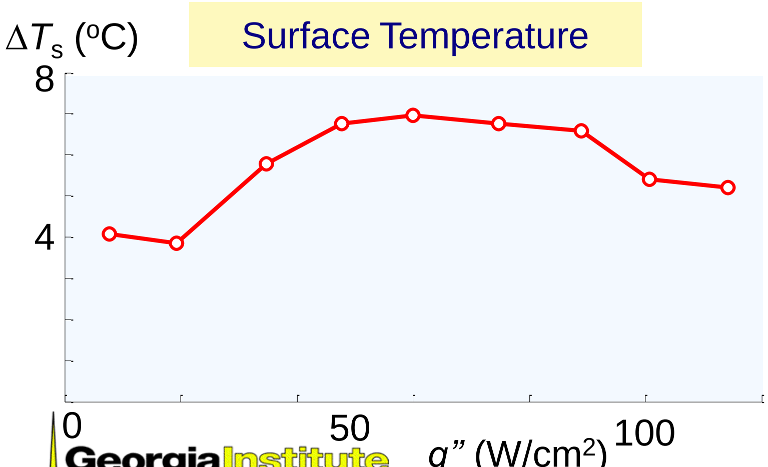


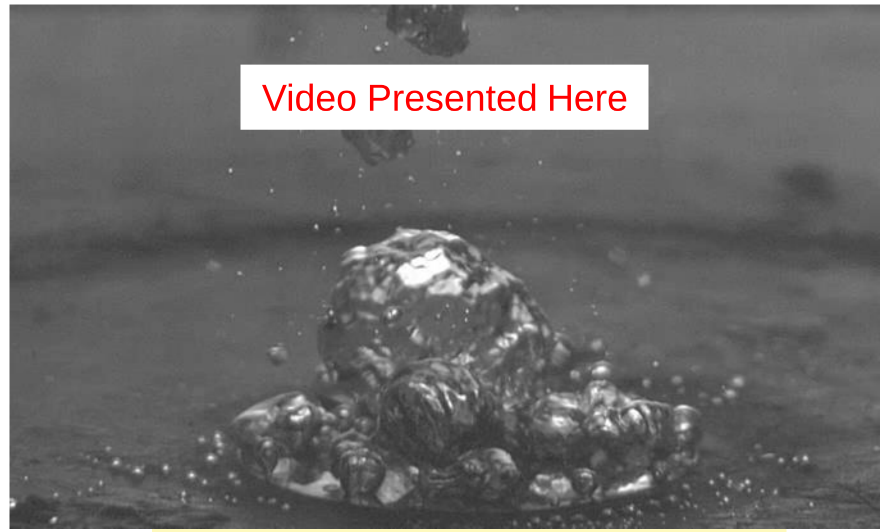
- Heated surface design
  - » Cartridge heater and thermocouples
  - » Exchangeable heater surfaces
    - – Plain
    - – Plain, instrumented with surface-soldered thermocouples
    - – Microchannel grid

Distilled water
1 atm
93°C bulk temperature

Ultrasonic Control of Vapor at Surface





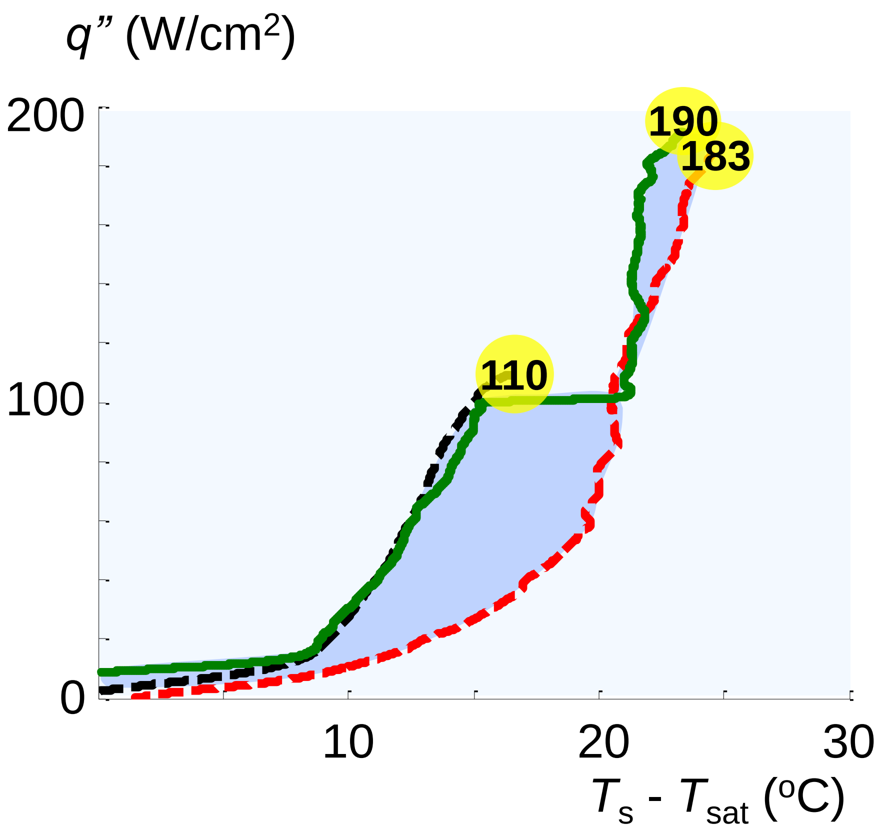


Vapor removal at surface
50 W/cm^2

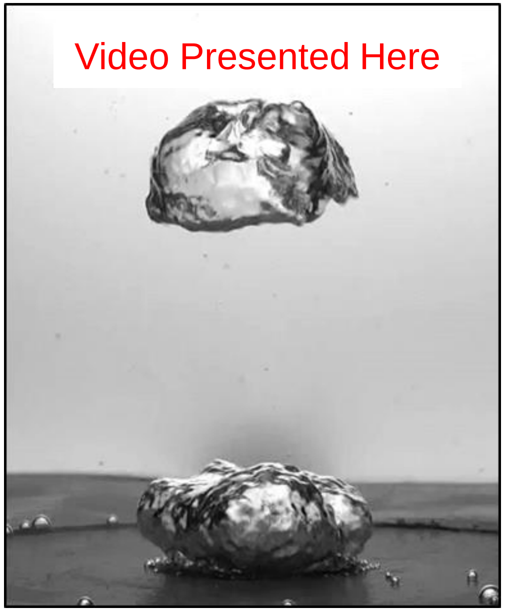
High-frequency acoustic actuation

- » Increases surface temperature (7 ^oC)
  - – Detaches small scale vapor bubbles
  - – Suppresses vaporization process at most nucleation sites
- » Increases CHF by 65%
  - – Agreement with wire experiments of Isakoff (1956)

Ultrasonic Control of the Boiling Curve



No Actuation



Acoustic Actuation
(1.7 MHz)

$q'' = 100$ W/cm^2

1 mm

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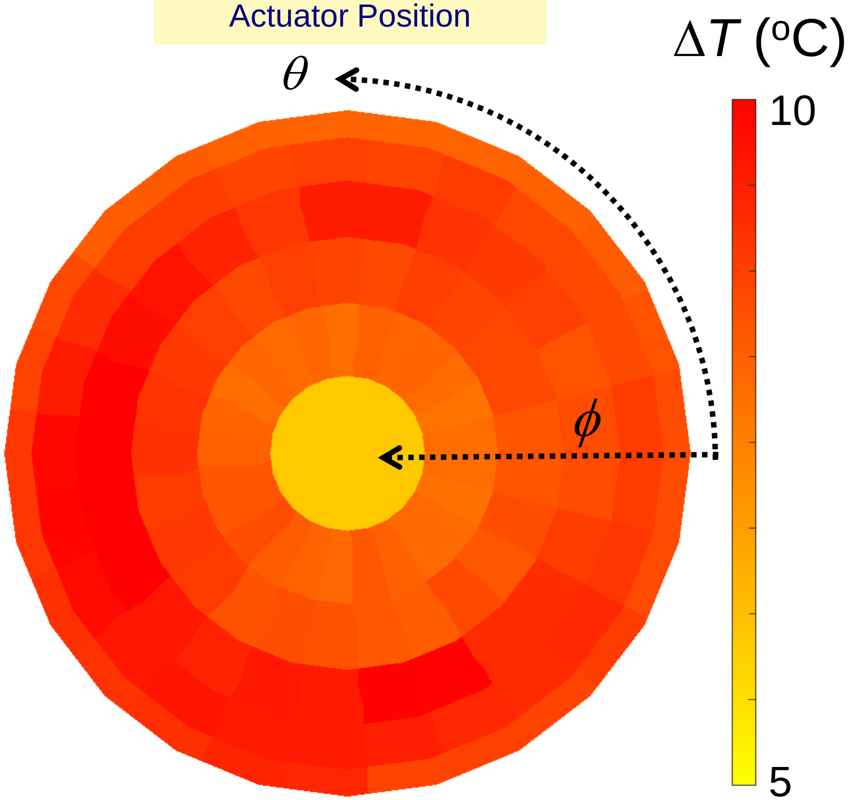
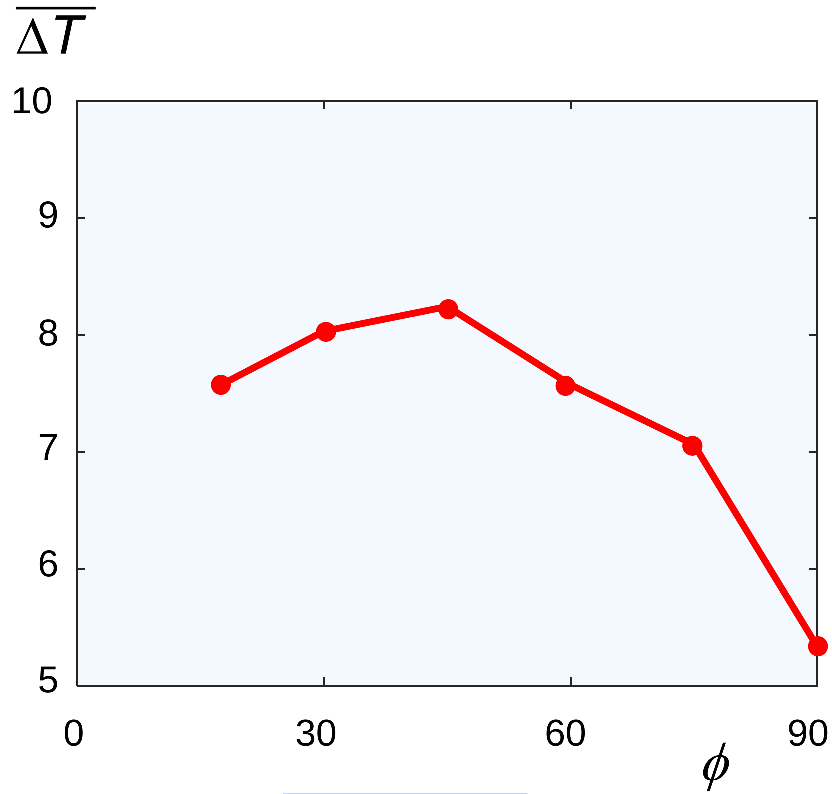
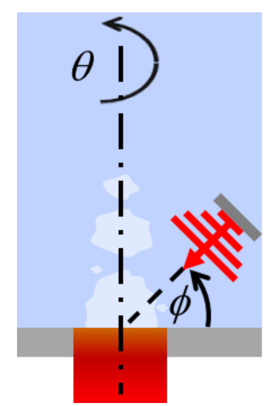
Effect of Actuator Incidence Angle

ΔT as function of Actuator Position

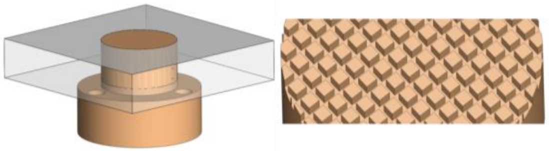






q''_{base} = 100 W/cm^2, T_{base} = 110°C, T_{bulk} = 93°C

microChannel Design: More than Surface Area

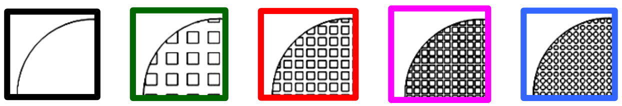


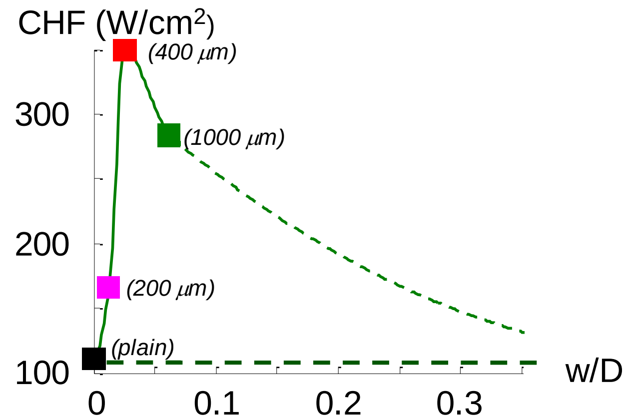
Smooth

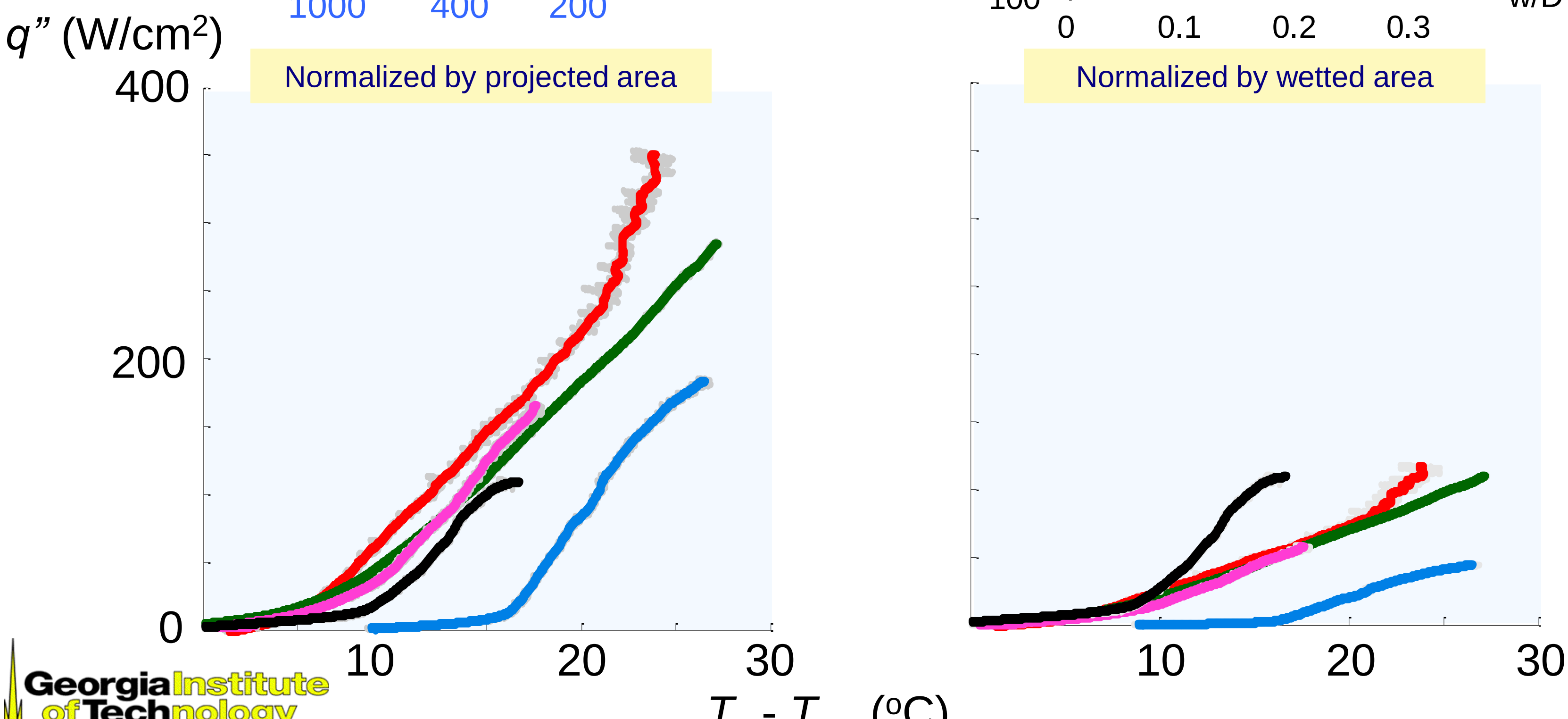
microChannels

Dimpled

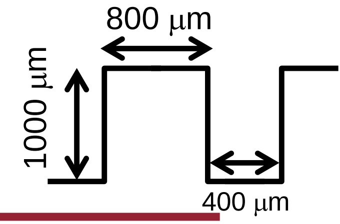
approx. same wetted area

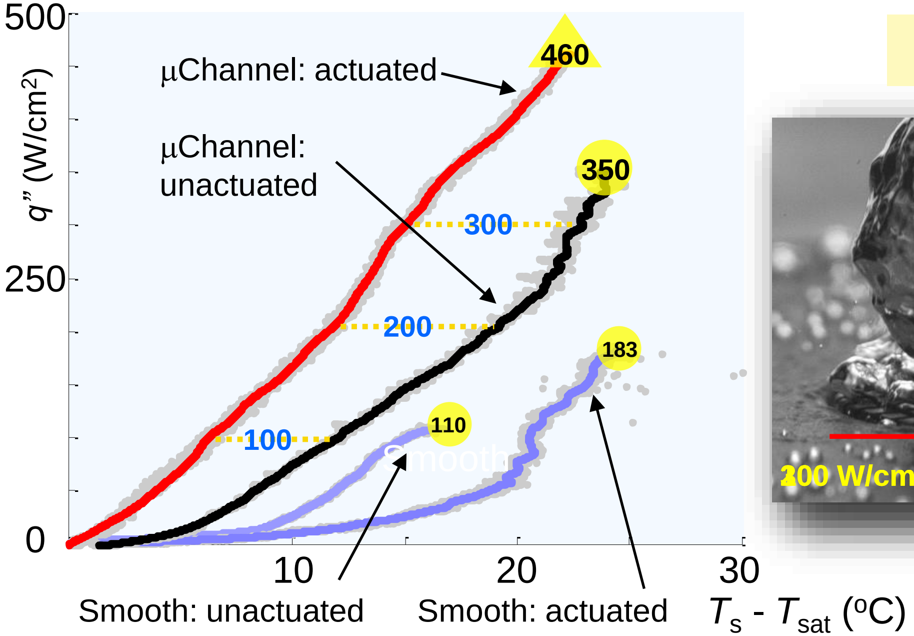


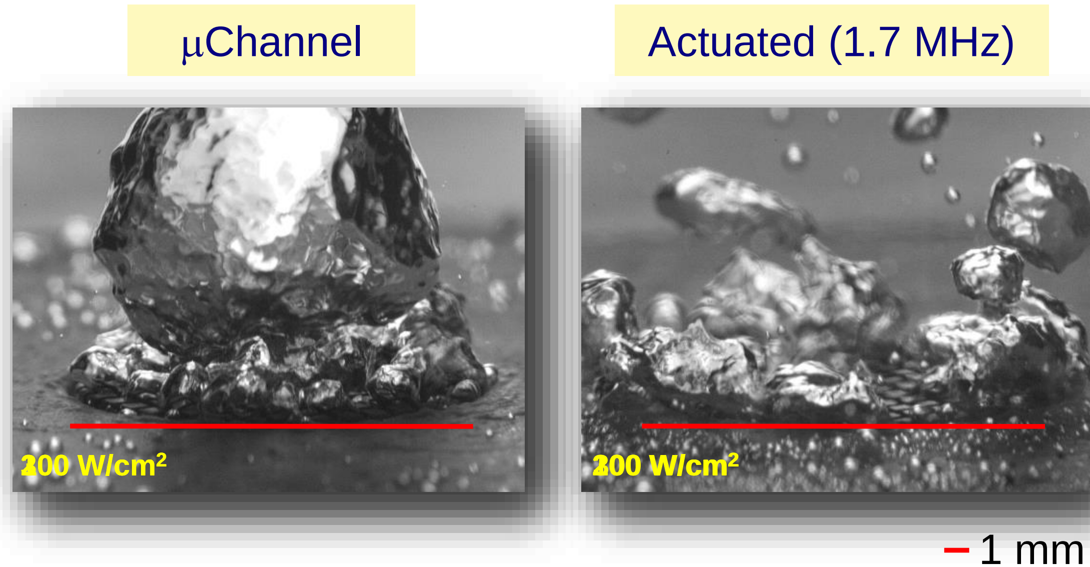


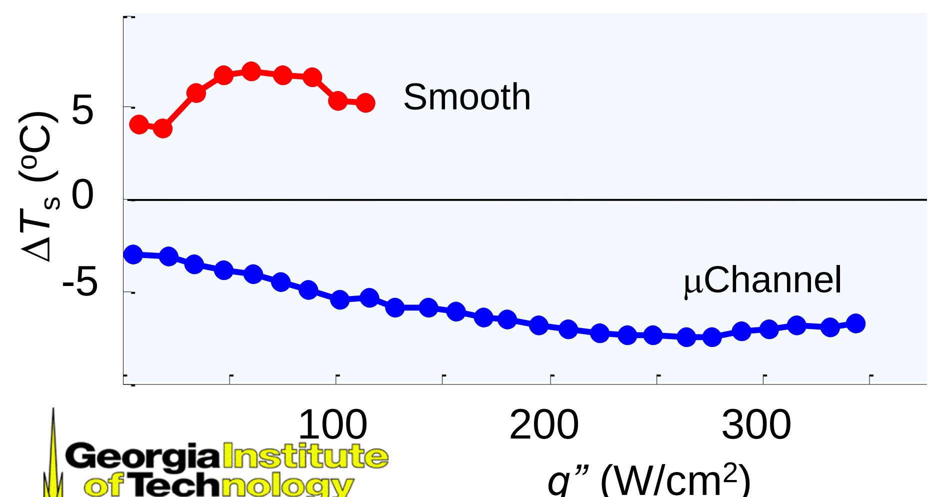


Surface µChannels with Ultrasonic Actuation





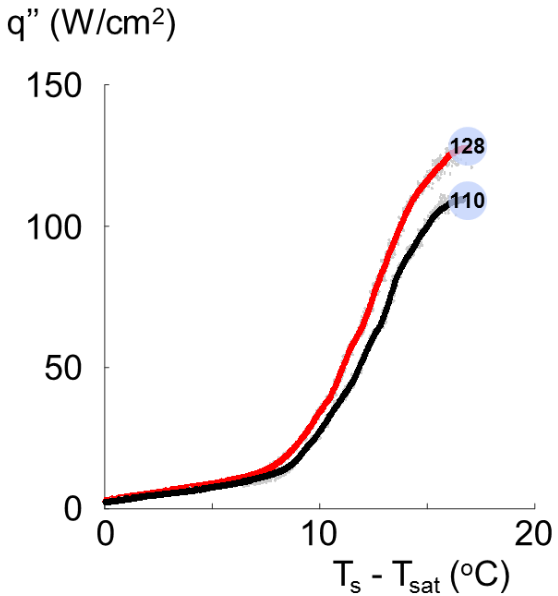


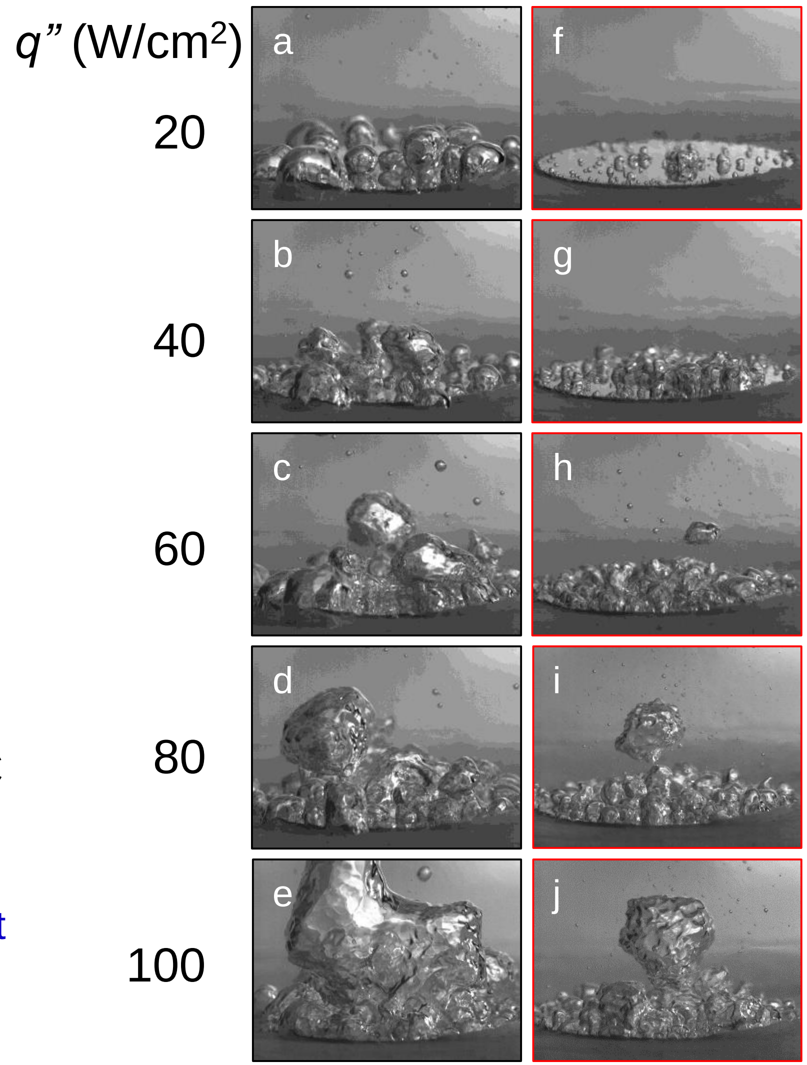


Small-scale acoustic actuation within µChannels

- » Decreases surface temperature (~ 7 °C).
- » Increased power dissipation $\Delta P \approx 200$ W/cm² at $T_s - T_{sat} = 17$ °C
- » Increases CHF by 31%
- » Decreases surface temperature fluctuations.
- » Increase CHF by 318% relative to smooth, unactuated case

O(1 kHz) Acoustic Enhancement of Boiling





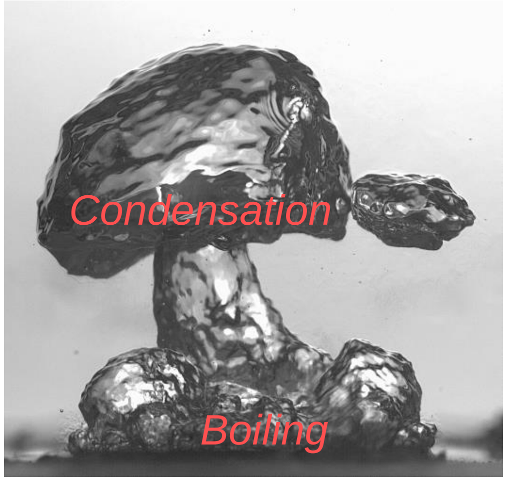
- Marginal increase in CHF (16%)
- Decrease in surface superheat of ~1 ^oC
- Appearance of vapor is markedly different due to surface capillary waves
  - » Increased condensation has minimal effect on boiling process

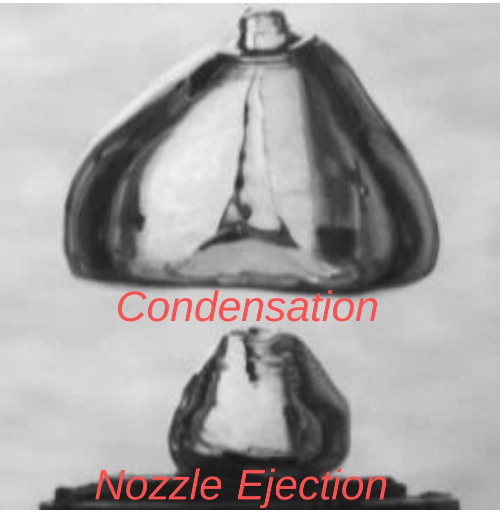
Acoustic Control of Vapor Condensation

- Pool boiling and condensers both require enhanced condensation
  » Pool boiling used in heat sink applications
    – Vapor boils and condenses in close proximity
  » Condensers used in power cycles
    – Vapor is injected; boiling occurs in separate boiler component
    – Nozzle geometry interacts with vapor formation and acoustic enhancement

- Condensation is limited by interface area
  » Thermal boundary layer surrounds vapor

1 mm





1 mm

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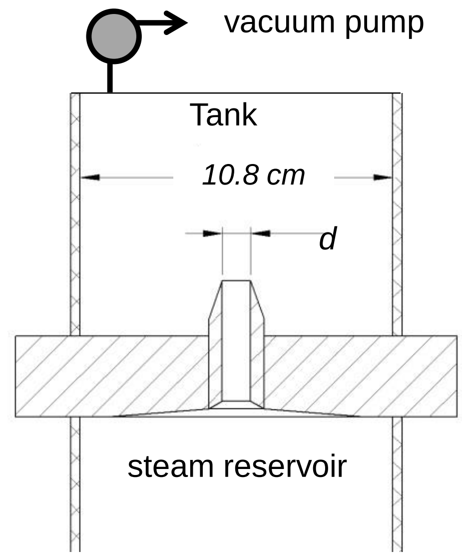
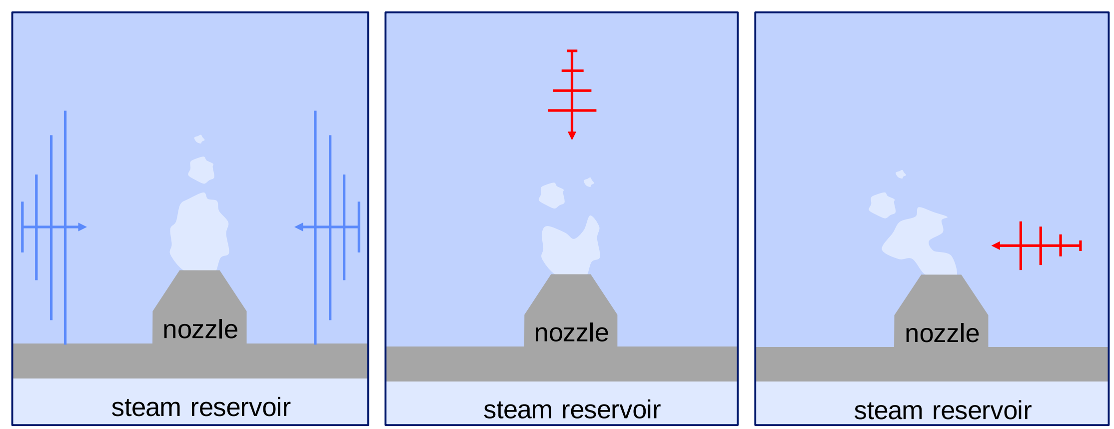
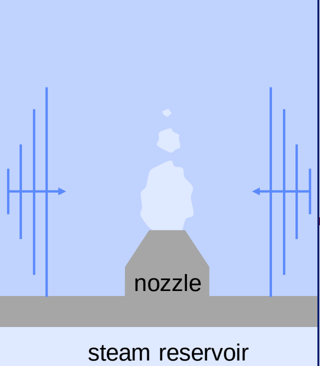
Acoustically Controlled Condensation Experimental Setup

- Vacuum pump sets the ambient pressure in test cell
- Middle plate separates boiling from condensation
  - » Nozzle geometry can be varied
  - » Bulk temperature of upper tank controlled with coil heat exchanger (not shown)
  - » Immersion heater creates vapor in lower tank
- Acoustic actuators:
  - » 1 kHz, placed to sides of nozzle
  - » 1.7 MHz, oriented either above or to side of nozzle



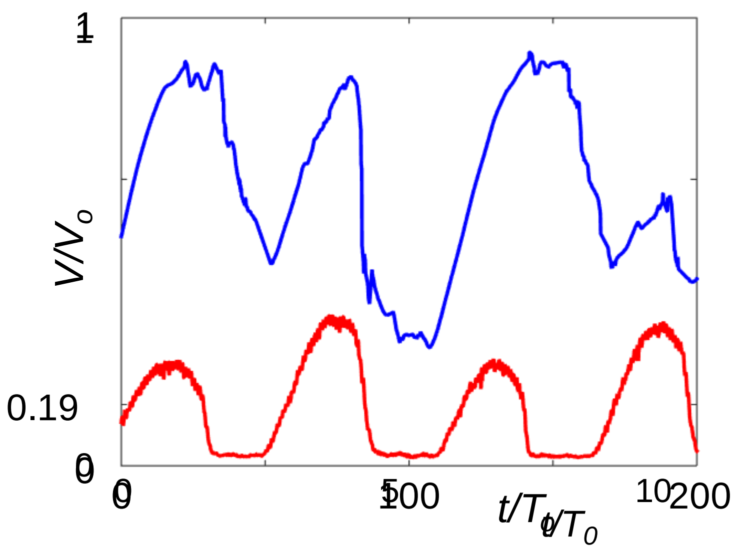
Distilled water
0.15 – 1 atm





Acoustically Enhanced Bubble Condensation
Low Frequency (1 kHz)

Increased thermal interfacial mixing leads to rapid collapse.



$$A* = \frac{\text{Vapor Area}}{\text{Average Baseline Vapor Area}}$$

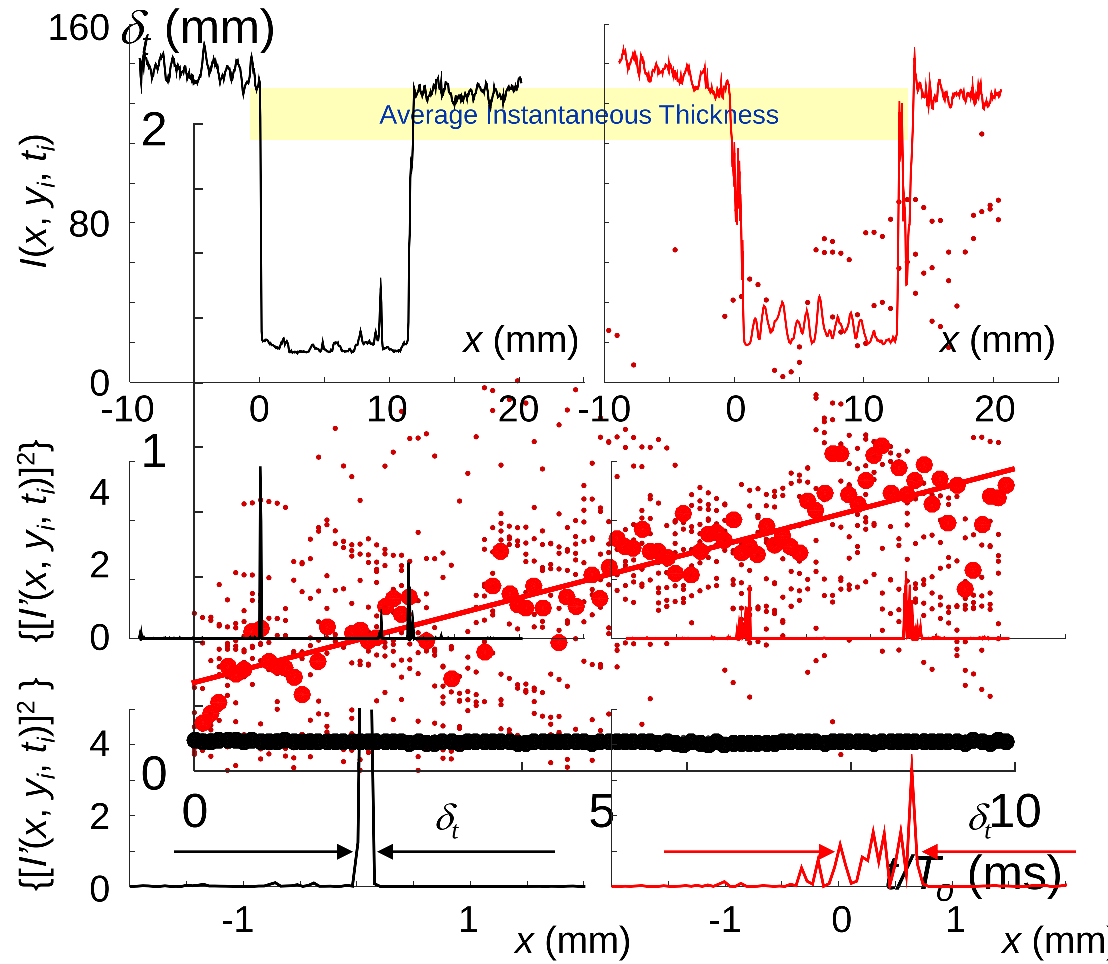
T_o: acoustic actuation period ≈ 1 msec

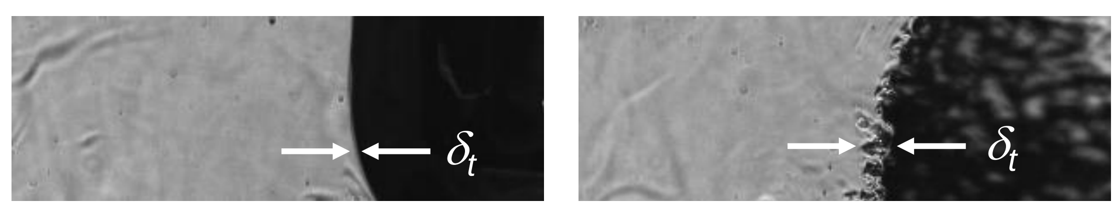
Base Flow	Actuated

25 ºC subcool 225 W
Continuous Actuation (Atmospheric Pressure)

Boundary Layer Growth - kHz Condensation

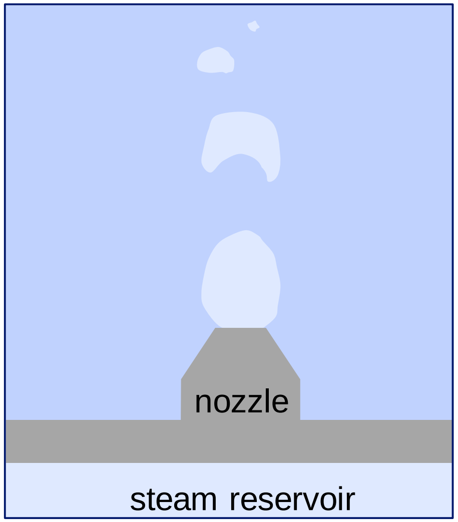
- Image processing of Schlieren images yields quantitative information on boundary layer growth
- Thermal boundary layer in baseline flow does not undergo appreciable growth
  - » Heat transfer occurs primarily through lower (and subsequently, inner) interface
- Acoustic actuation leads to nearly linear growth of boundary layer thickness
  - » No significant temporal dependence on acoustic actuation
- Thermal boundary layer in presence of acoustic actuation is on average 6.7 times thicker
  - » Up to 17 times thicker

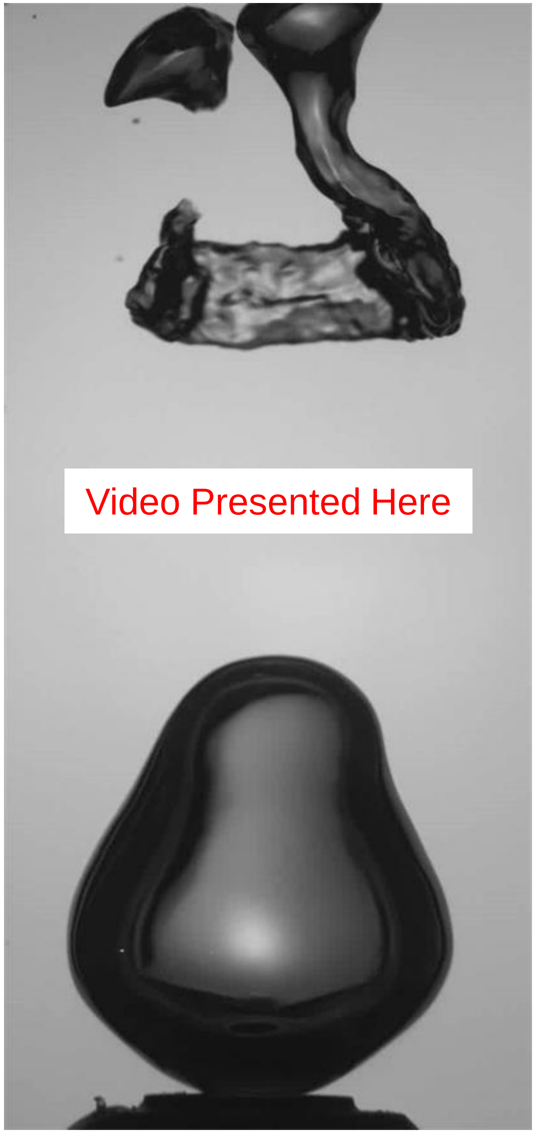




Natural Deformation-Induced Vapor Collapse

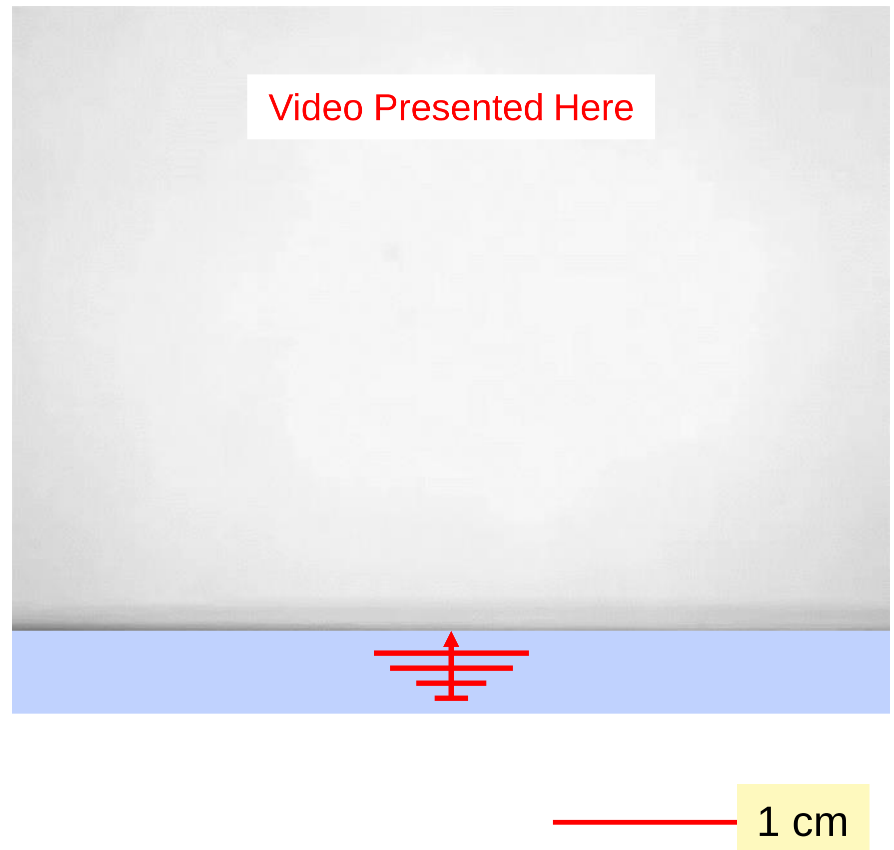
- Surface tension pinch-off drives a liquid “spear” through the center of the vapor bubble to form a vapor torus that leads to rapid condensation.
- Schlieren imaging shows insignificant thermal gradients in fluid surrounding bubble.
  - » Inner “spear” enhances heat transfer
- This natural mechanism indicates that inducing such a liquid “spear” early in the bubble formation process can lead to accelerated condensation.





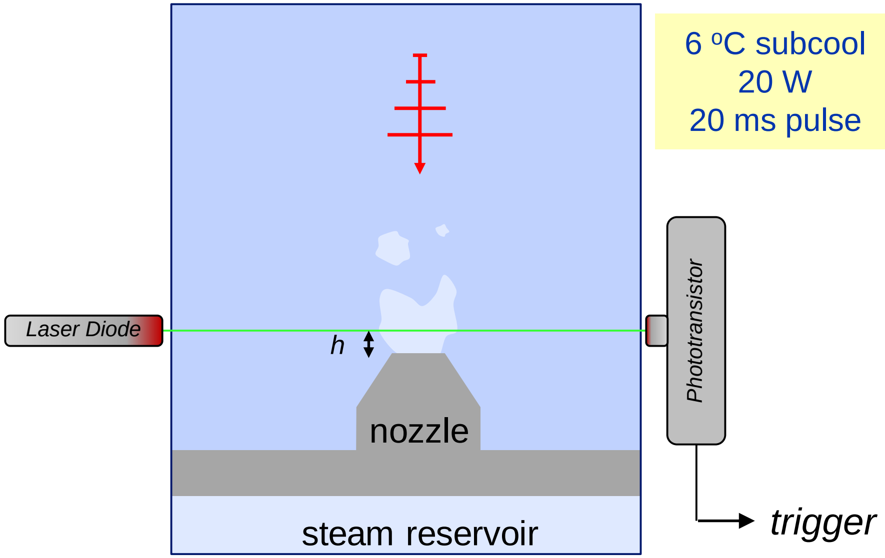
Ultrasonic Liquid-Gas Interfacial Actuation

- $f = 1.7$ MHz
  - $\lambda_{acoust} = 0.9$ mm; $D_{res} = 2$ μm
  - $\lambda_{capillary} = O(\mu m)$
  - "Mist" droplets ejected, visible in video
- Cavitation and subsequent collapse generates additional droplets
  - Larger-scale; not uniformly sized
- Acoustic impedance mismatch
  - $Z_{vapor}/Z_{water}=1.8x10^{-4}$
  - Surface deforms from acoustic pressure
    - Deformed surface self-focuses acoustic intensity

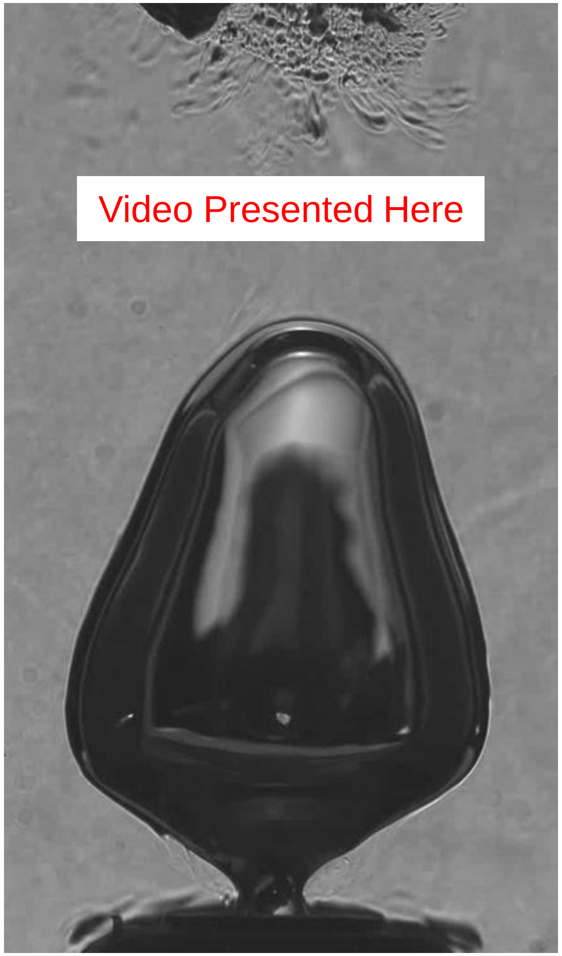


Condensation Enhancement: Pulsed Ultrasound

Significant savings in actuation power

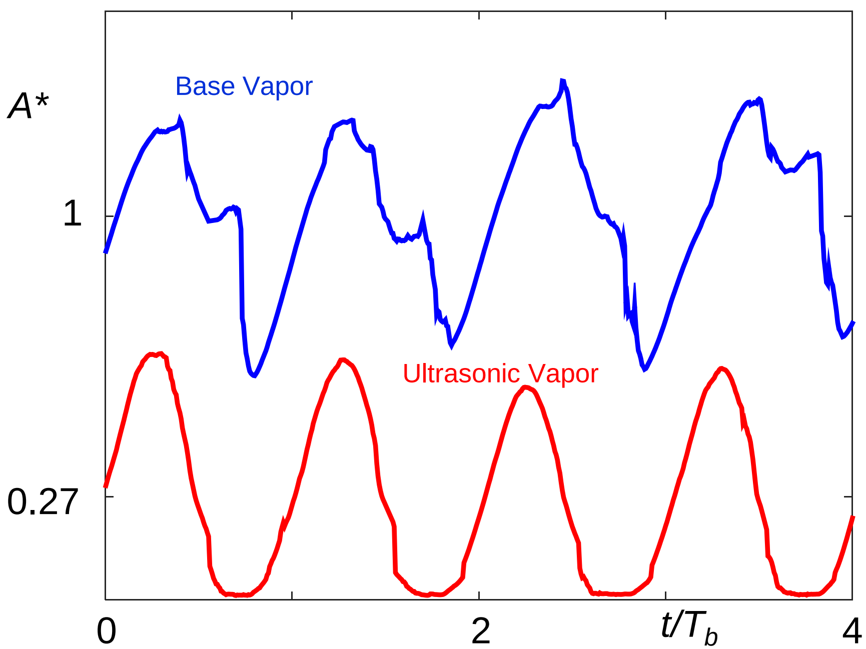


Schlieren Imaging

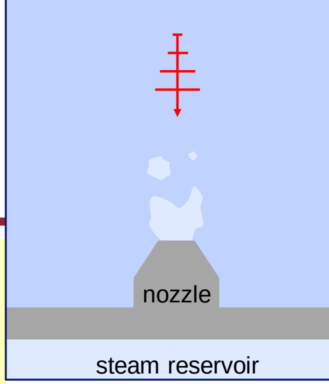


- Pulsed actuation.
  - » Saves power
  - » Minimizes interference with vapor ejection
  - » Vapor ejection pressure remains unchanged
- Pulse actuation is synchronized to "natural" bubble formation.
  - » Bubble phase reference is obtained using a trigger laser beam at given height above nozzle
  - » Actuation wavefronts are monitored using Schlieren imaging

Axially-Aligned Pulsed Ultrasound Actuation



Triggering laser diode
5 mm above nozzle
Q = 225 W
T_b = 50 ms
Subcooling = 25 °C



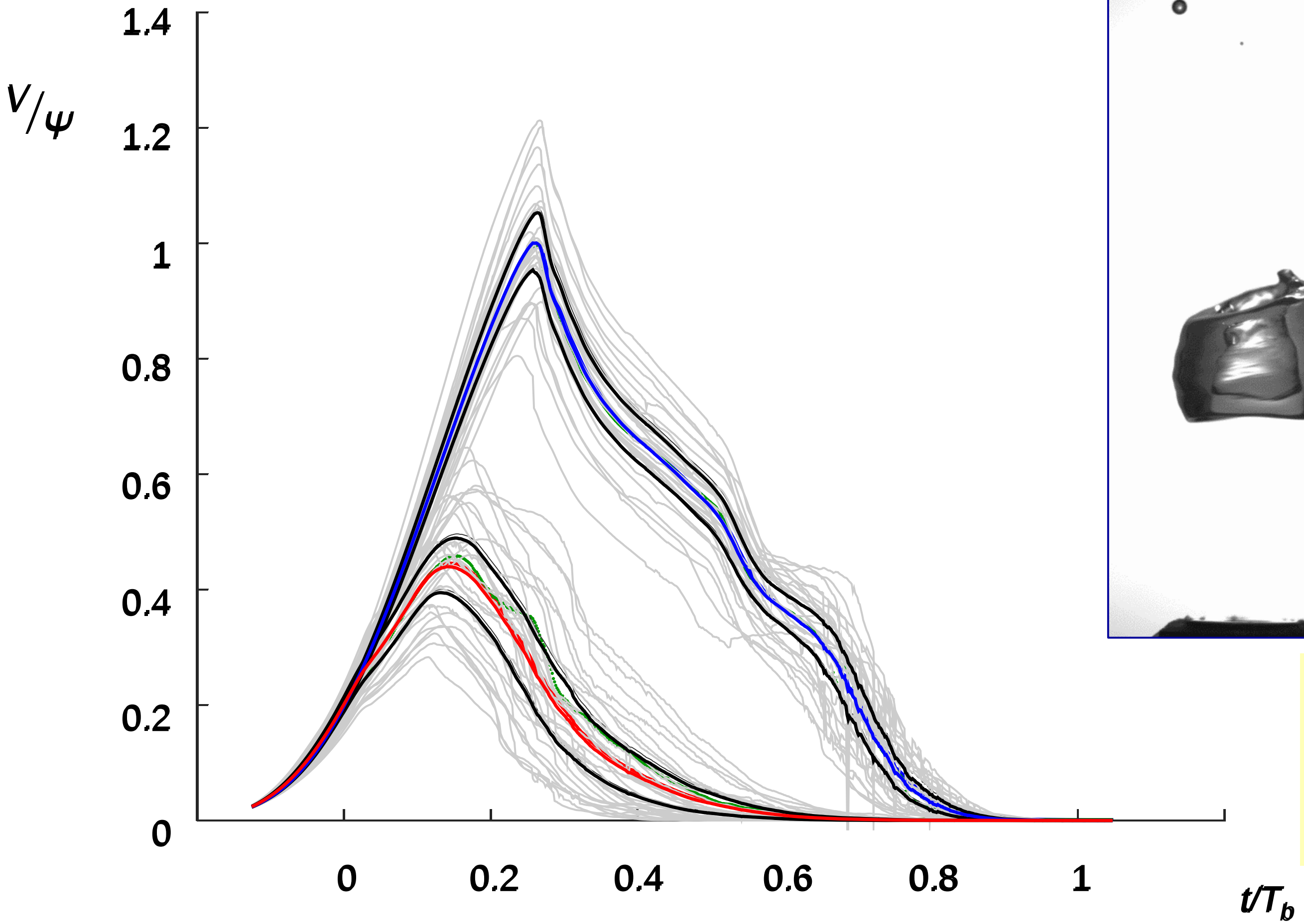
- High-speed video image processing yields an estimate of total vapor domain as function of time.
  - » Subcooling and heater dissipation are invariant, leading to the relation between vapor domain and heat transfer coefficient.

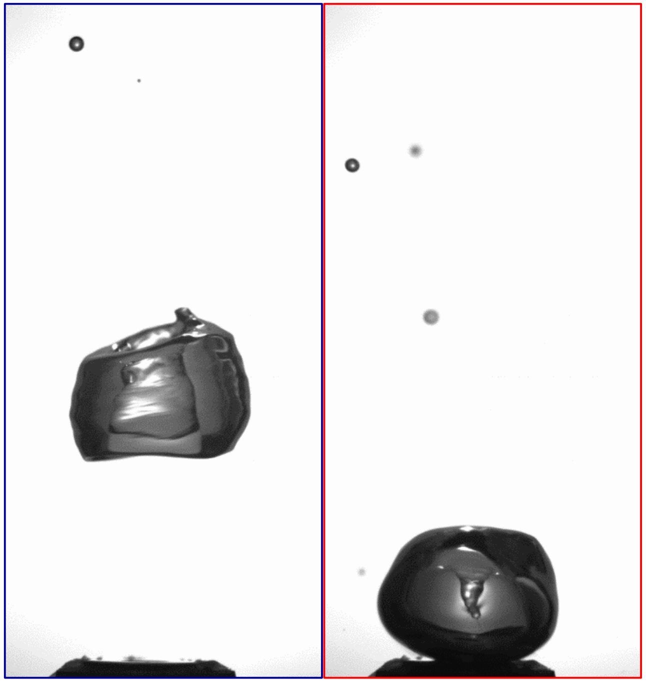
$$q_{base} = U_{base,eff} A_{base,eff} (T_{sat} - T_s) = UA_{act,eff} (T_{sat} - T_s) = q_{act}$$

$$\xrightarrow{yields} \frac{U_{act,eff}}{U_{base,eff}} = \frac{A_{base,eff}}{A_{act,eff}}$$

- Vapor domain reduced by up to 73% using 20 ms actuation pulses.
  - » HTC increased by 270%
- Actuation “regularizes” time-periodic bubble formation.
  - » The base flow a new bubble is ejected while the earlier bubble collapses
  - » In the presence of actuation, bubble collapse is completed prior to ejection of the subsequent bubble

Bubble Volume Tracking

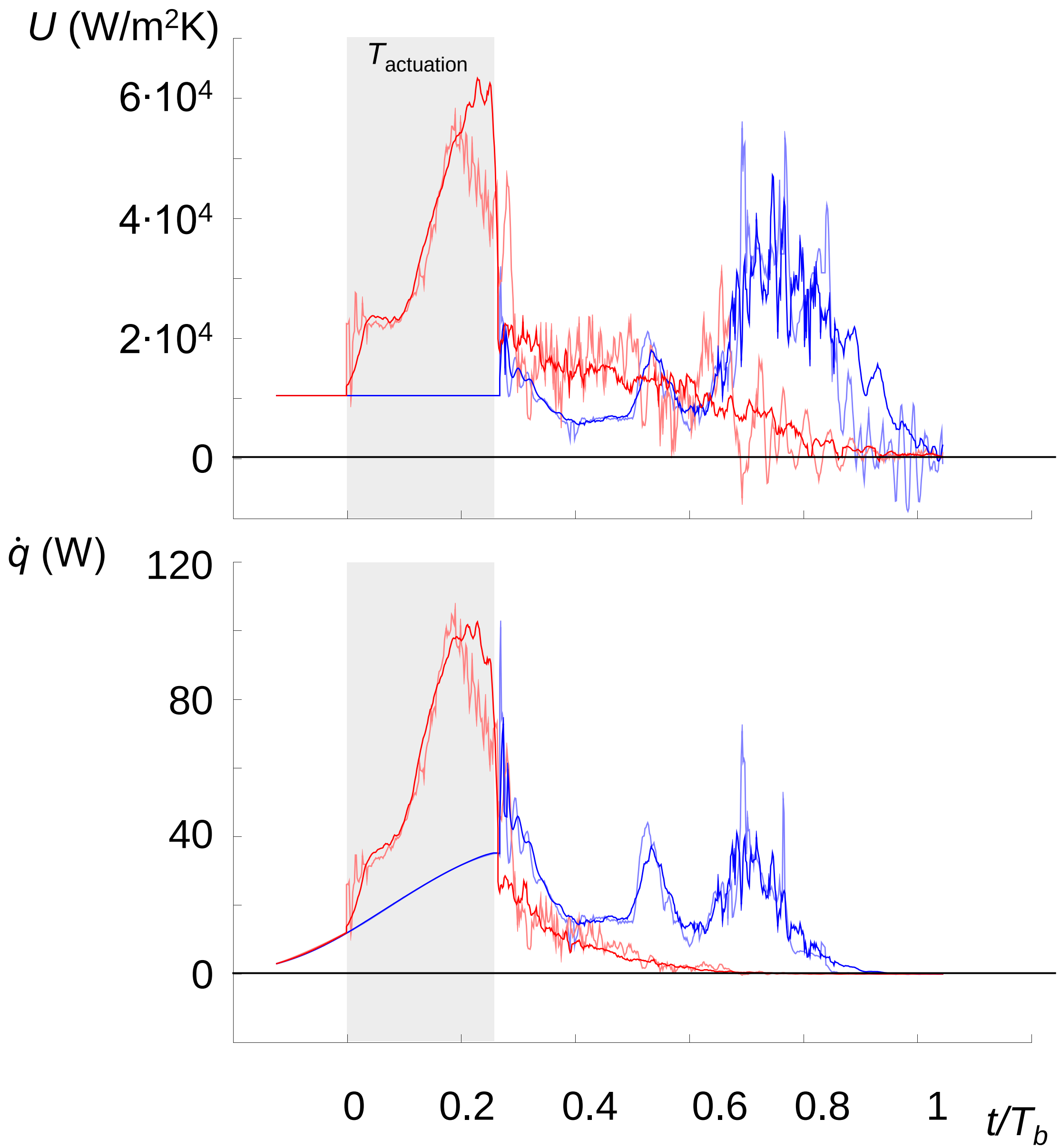




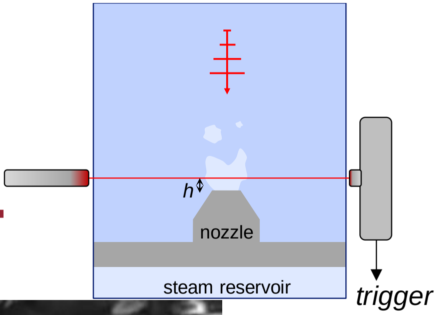
8 °C subcool
20 W
20 ms pulse
T_b = 80 ms
Ψ = 0.822 cc

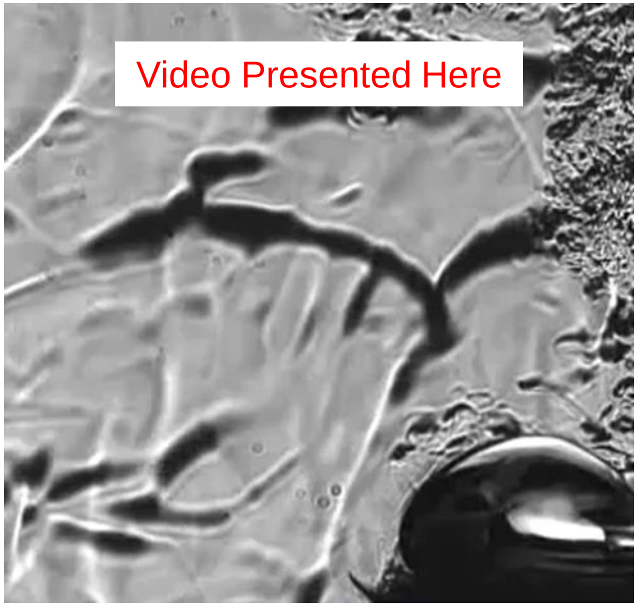
Temporal Variation:
Heat Transfer Coefficient and Heat Rate

- Peak heat transfer coefficient occurs during toroidal breakup in the absence and presence of actuation.
  - » Acoustic actuation leads to near-immediate doubling of HTC
- Peak heat rate occurs during pinch-off, torus formation, and toroidal breakup
- Non-spherical effects
  - » Lower peaks and higher troughs

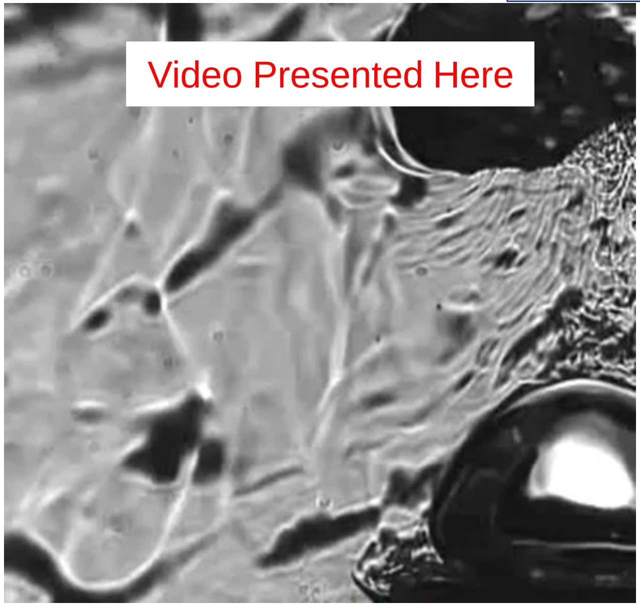


Interfacial Disturbances by Secondary Droplet Ejection





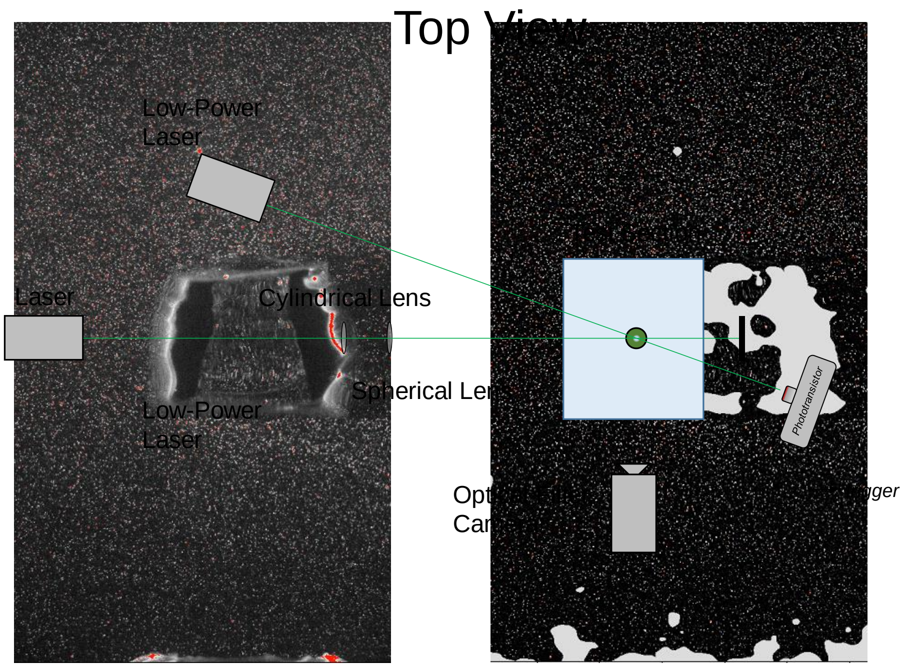
Base Flow

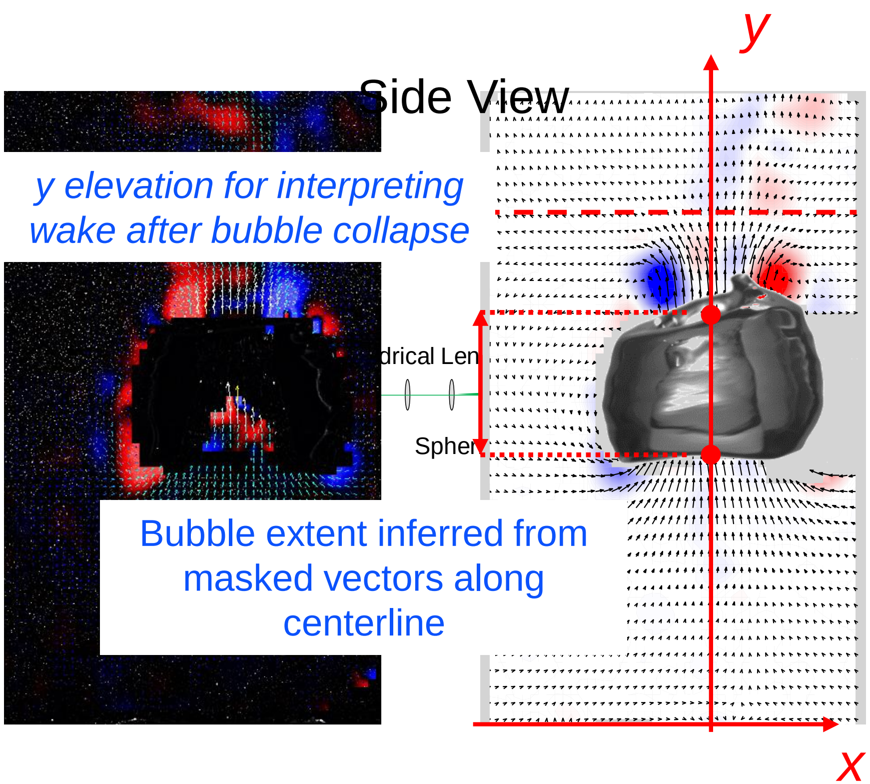


Pulsed Ultrasound Actuation

- High-resolution Schlieren imaging reveals formation of ultrasonically induced droplet ejection from spear.
- Required mass for complete phase change:
  $m_{droplets} = E/(c_p \cdot \Delta T) = [(V_o/v_g) \cdot h_{fg}]/(c_p \cdot \Delta T)$
- $m_{droplets}$ *per pulse:* 0.0207 gram/pulse.
  - Can contribute up to 60% at low subcooling (8 ^{o}C), small bubbles or 45% at high subcooling (25 ^{o}C), large bubbles

Particle Image Velocimetry

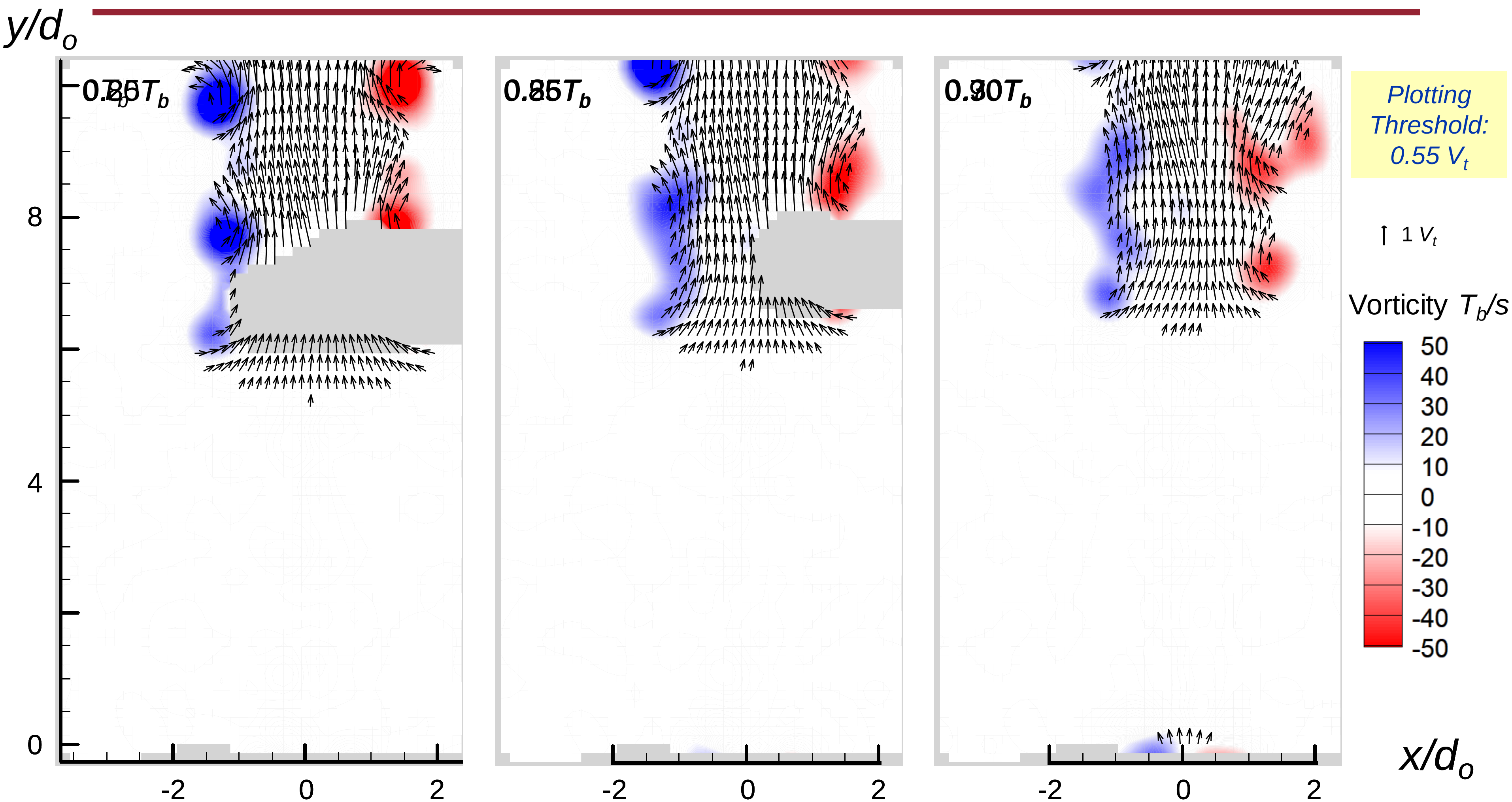




- Fluorescent Particles and optical filter to reduce laser reflections
- Algorithmic masking to remove interface/ non-particle-laden flow
- Post processing: 10,000 fps flow fields temporally averaged over 0.5 ms (5 frames)
  - » Rightward of bubble is masked to remove interior and bubble shadow

8 °C subcool, 20 W, 20 ms pulse

Naturally Condensing Vapor Bubbles



V_t = 0.55, T_b = 80 msec, d_o = 2.3 mm

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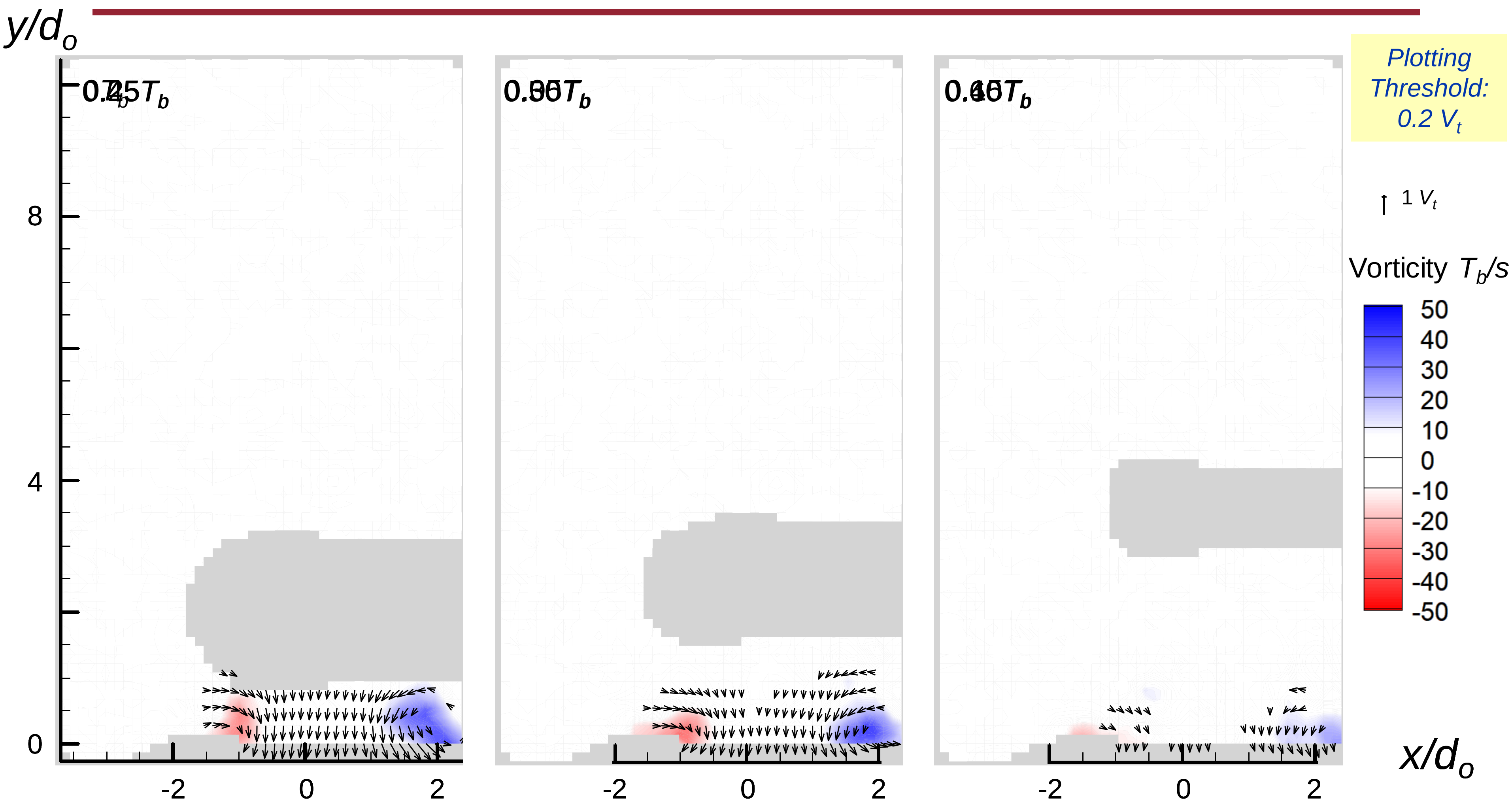
Acoustically Actuated Vapor Bubbles



V_t = 0.55, T_b = 80 ms, d_o = 2.3 mm

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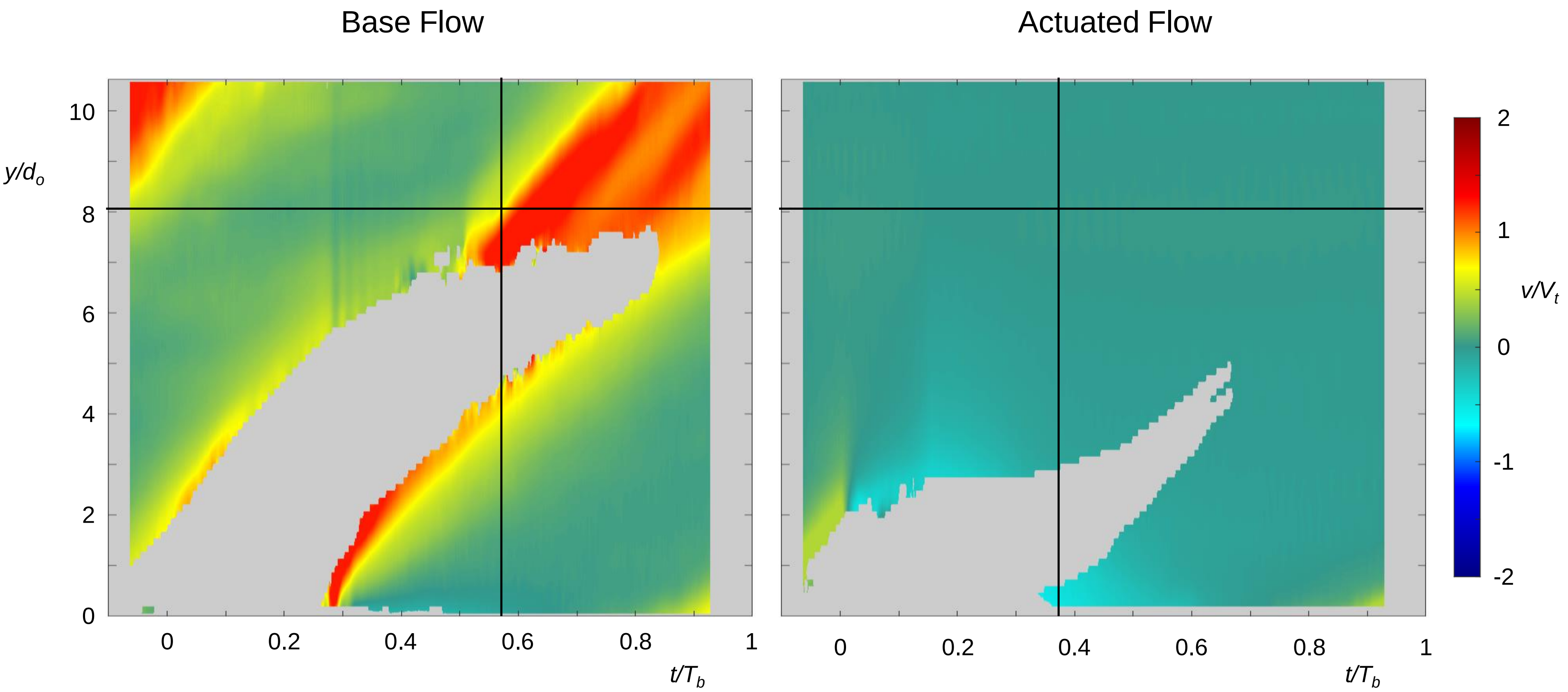
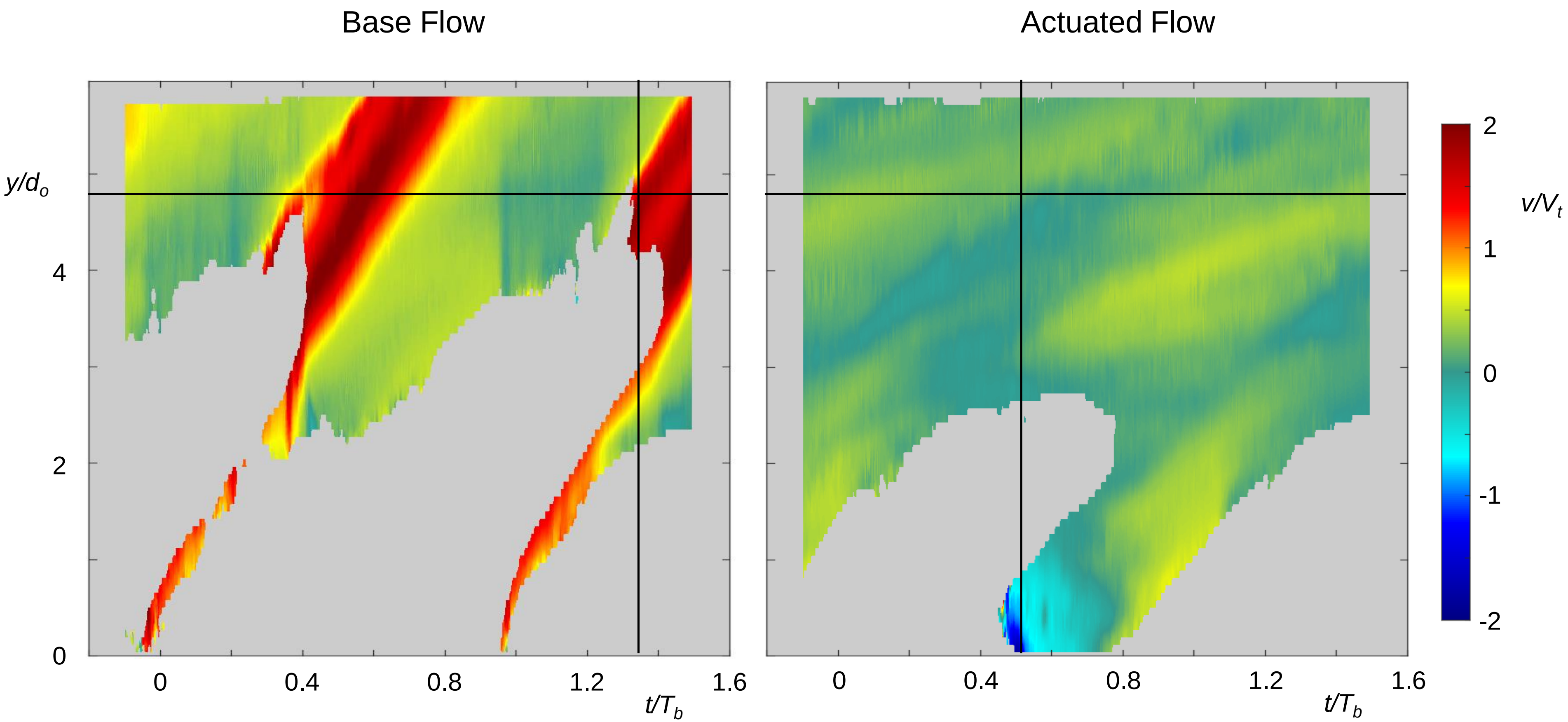
Centerline Velocity



T_b = 80 ms, V_t = 0.55 m/s, d_o = 2.3 mm

High-Subcooling, High-Mass Flow Rate Vapor



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T_b = 50 ms, V_t = 0.70 m/s, d_o = 5.3 mm

General Conclusions

- Acoustic actuation is an effective method for controlling two-phase flows with heat transfer.
  - » Interfacial coupling varies with actuation wavelength
    - – Low frequency, O(1 kHz); long wavelength = 1 m
    - – High frequency, O(1 MHz); short wavelength = O(1 mm)
  - » The acoustic coupling forces liquid-vapor interfacial motion that affects vapor formation, advection, and condensation.
  - » Strongly enhances pool boiling heat transfer.
  - » Accelerates direct-contact vapor condensation.

Conclusions: Boiling

- Ultrasonic actuation (short wavelength).
  - Couples to vapor bubbles by a surface force.
  - Vapor bubble nucleation, growth, and detachment are modified.
  - CHF increases by 65%; surface temp. increases by 7 °C.
  - Condensation increases above the boiling surface.
  - Actuation may be turned on and off as needed without a drop in performance.
- Textured surfaces with ultrasonic actuation.
  - Microchannels alone increase CHF to 350 W/cm^2.
    - Ultrasound increases CHF to 460 W/cm^2.
  - Ultrasound *reduces* surface superheat by 7 °C (in contrast to smooth heater).

Conclusions: Condensation

- O(1 kHz) acoustic actuation (long wavelength).
  - » Interfacial Faraday waves increase condensation in the bulk liquid.
  - » Interface motion induces a temporally-growing thermal boundary layer.
  - » Condensation rate is increased both during growth and after advection, with increases of up to 425% in the time-averaged overall heat transfer coefficient.
  - » Importance of motion in inducing mixing implies effectiveness scales with surface displacement.
    - – Lower frequencies (1 kHz or below).
    - – Prior work used either extremely low (50 Hz) or high (20 kHz) frequencies, with smaller improvements in HTC.
- Ultrasonic acoustic actuation (short wavelength).
  - » Subcooled liquid jet protrudes into vapor bubble, significantly increasing vapor surface area and heat transfer coefficient.
  - » Formation of toroidal volume leads to rapid bubble collapse.
  - » Pulsed actuation causes up to a 73% reduction in vapor extent.